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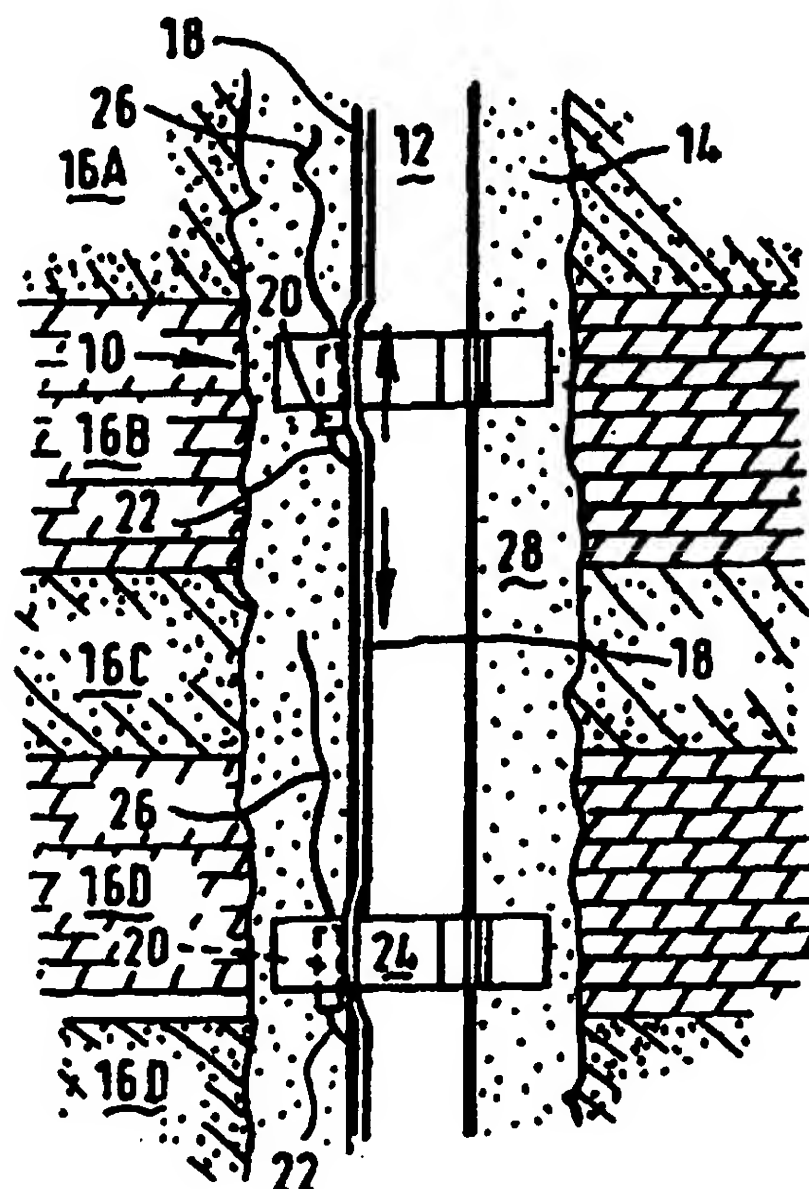
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(54) Title: METHOD AND SYSTEM FOR MONITORING A CHARACTERISTIC OF AN EARTH FORMATION IN A WELL

(57) Abstract

A system is provided for monitoring a characteristic of an earth formation into which a wellbore is formed with a casing (12) fixed in the wellbore (14) by a layer of cement (28) between the casing and the wellbore wall, said characteristic being transferable through at least part of the thickness of the cement layer. The system comprises at least one sensor (20) for measuring said characteristic, each sensor being attached to the casing and including sensing means (26) extending into the layer of cement, and means for transferring signals representing said characteristic from the sensor to a selected surface facility.



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**METHOD AND SYSTEM FOR MONITORING A CHARACTERISTIC OF AN EARTH FORMATION IN A WELL**

The present invention relates to a method and system for monitoring an underground formation intersected by a borehole. In a preferred embodiment the present invention relates to a method and system for  
5 simultaneously monitoring multiple zones of a formation along a borehole.

Current and reliable information regarding conditions at zones of a formation can aid in completing wells, reservoir management, and secondary recovery operations.  
10 In such applications a borehole is drilled to cross multiple zones of a formation. One or more of the intersected zones may contain hydrocarbon bearing strata with reserves in recoverable form and quantity. However, other zones may also be of interest in well management.

Commercial services provide "repeat formation testing" in which a wireline tool is run and multiple readings are taken as the tool is retrieved. This does provide data on multiple zones, but the information is not truly simultaneous and is collected only  
15  
20 intermittently.

Thus, there remains a clear need for a method and system for providing continuous and simultaneous readings from one or more zones of an earth formation.

In accordance with one aspect of the invention there is provided a system for monitoring a characteristic of  
25 an earth formation into which a wellbore is formed with a casing fixed in the wellbore by a layer of cement between the casing and the wellbore wall, said characteristic being transferable through at least part of the thickness  
30 of the cement layer, the system comprising:

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- at least one sensor for measuring said characteristic, each sensor being attached to the casing and including sensing means extending into the layer of cement; and

- 5       - means for transferring signals representing said characteristic from the sensor to a selected surface facility.

      In accordance with another aspect of the invention there is provided a method of monitoring a  
10       characteristic of an earth formation into which a borehole is formed, the method comprising:  
      a) attaching at least one sensor having sensing means for measuring said characteristic to a casing which is to be installed in the borehole, the sensing means being  
15       arranged such as to extend between the casing and the borehole wall when the casing is installed in the borehole;  
      b) providing means for transferring signals representing said characteristic from the sensor to a selected surface  
20       facility;  
      c) lowering the casing into the borehole;  
      d) selecting a cement for cementing the casing in the borehole so that said characteristic is transferable through at least part of the thickness of the cement  
25       layer formed when the casing is cemented in the borehole;  
      e) cementing the casing in the borehole whereby the sensing means becomes located in the cement layer between the casing and the borehole wall.

      By locating the sensing means in the cement layer  
30       through which the characteristic to be monitored is transferable it is achieved that each sensor is in close proximity with the earth formation while at the same time the sensor can be installed in an attractive manner and is protected adequately by the cement layer.

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Suitably said characteristic is at least one of the formation pressure, the formation temperature and the formation fluid composition.

5 Preferably the system comprises a plurality of said sensors spaced along the casing.

It is preferred that said means for transferring signals comprises a communications line extending along the casing to said surface facility, each sensor being connected in communication with the communications line.

10 The system and method of the invention is particularly suitable for measuring formation pressure over time, in which case said at least one sensor includes a pressure sensor for measuring the formation pressure.

15 To monitor multiple zones, a plurality of said pressure sensors is spaced along the casing, wherein the sensing means of the plurality of sensors are separated by a distance along the borehole such that the sensors are relatively insensitive to axial pressure transmission through the cement when compared to radial pressure transmission from the wellbore to the sensing means.

20 In order to reduce axial pressure diffusion in the cement, the hydraulic diffusivity of the cement and the spacing of the sensing means are adjusted such that the time scale for pressure communication from the formation to the sensing means is small compared with communication between adjacent sensing means.

25 Axial pressure diffusion in the cement is further reduced if the hydraulic diffusivity of the cement is less than that of the formation.

30 The brief description above, as well as further advantages of the present invention, will be more fully appreciated by reference to the following detailed description of the preferred embodiments which should be

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read in conjunction with the accompanying drawings in which:

5 Fig. 1 is a side elevational view of a distributed pressure monitoring system in accordance with the present invention;

Fig. 2 is a perspective view of a single pressure sensor mounted to a casing;

Fig. 3 is an axially cross sectioned view of the pressure sensor of Fig. 2 as taken at line 3-3 in Fig. 2;

10 Fig. 4 is a cross sectional view of the pressure sensor of Fig. 3 taken along line 4-4 of Fig. 3;

Fig. 5 is a side elevational view illustrating installation of a distributed pressure monitoring system;

15 Fig. 6 is a graph illustrating data collected by monitoring multiple zones during successful cementing operations for a well;

Fig. 7 is a graph illustrating data collected by monitoring multiple zones during cementing operations for a well which was predicted to require remedial actions;

20 Fig. 8 is a graph illustrating data of pressure drop as a function of time;

Fig. 9 is a graph illustrating pressure propagation modelled for a particular well as a function of change in pressure, time, and cement permeability;

25 Fig. 10 is a graph illustrating results of modelling pressure response as a function of time, distance and permeability for pressure transmission from a selected zone to an adjacent sensor; and

30 Fig. 11 is a graph illustrating results of modelling pressure response as a function of time, distance and permeability for pressure transmission through the cement between pressure sensors.

35 A distributed monitoring system 10 is illustrated in Fig. 1 mounted to the exterior of casing 12. The casing is run within borehole 14 which intersects multiple

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zones 16A-16E in the illustrated interval. A communications line 18 runs along the casing and branches off to sensors 20 at pigtails 22. The sensors are mounted to the casing at protectors 24 which protect both the sensors and the communication line during installation. Sensors, here pressure sensors 20, are provided with open pressure tentacles 26. A cement 28 fills the annulus between the borehole wall and the casing.

Protector 24 is a modified centralizer mounted on casing 12. Fig. 2 illustrates pressure sensor 20 mounted and pinned between adjacent vanes 30 of protector 24. The communications line is attached to casing 12 with straps or ties 32 and is also protected from contact with the borehole wall when casing 12 is lowered into place. See also Fig. 3.

Communication may be provided through telemetry or through a communications line 18 as may vary in accordance with the sensor and transmission needs. Those having skill in the art will understand the present invention to have application across a wide variety of sensor needs. Potential applications include pressure, temperature, and fluid composition sensors. If a communications line 18 is deployed, it may be a multiple wire or multiline cable bundling a plurality of discrete wires. Alternatively, a fiber optic bundle may be used. In some embodiments, communications line 18 may even be formed with a bundle of capillary tubes, e.g., to transmit pressure directly from a sensor input element in the form of an open end with a fluid interface which communicates with surface sensors through an inert fluid in the capillary tube. In other applications it may be desired to monitor fluid composition with an infra-red or IR sensor to determine the oil, gas, and water makeup of current formation fluids. However, for the purposes of

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illustration, an embodiment of the invention is disclosed for monitoring pressure and, optionally, temperature. These are two parameters which are traditionally of great interest in reservoir management.

5        In this embodiment, communications line 18 is formed by multiline cable 18A, with each pigtail 22 connecting one of the sensors to a discrete wire within the cable.

10        Fig. 4 is a schematic illustration cross sectioning sensor 20. Here, sensor 20 carries a pressure transducer 20A and a temperature sensor 20B within sensor housing 34. The pressure transducer and temperature sensor forward signals to the surface through pigtail 22 and multiline cable 18A. Pressure transducer 20A samples the formation pressure through open pressure tentacle 26 in the form of stainless steel wire mesh hose 36 which is packed with gravel 38, which pressure tentacle 26 is in communication with pressure transducer 20A via a conduit 39. A frit 40 separates tentacle 26 from pressure transducer 20A and the frit allows formation pressure to pass and impinge upon silicone grease pack 42 in the conduit 39, and therethrough upon diaphragm 44 of pressure transducer 20A. However, the frit is also instrumental in separating the overburden pressure from the formation pressure.

25        Fig. 5 illustrates installation of a distributed pressure monitoring system. Multiline cable 18A arrives for installation spooled. In the illustrated embodiment, it is spooled with fluid blockers 46, pigtails 22 and repair sleeves 48 positioned to connect to sensors along the casing upon installation. The fluid blockers are lengths of pipes sealed tightly about the cable. These pipe lengths create a superior bond with the cement and prevent fluid migration between sensors 20 along communication line 18. The repair sleeves facilitate repair should the cable be damaged in handling. In that

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event, the breech is filled with resin and the sleeve slides into position thereover and is clamped and/or glued in place to secure the seal. The spooled cable is fed over a sheave 50 and cable 18A is tied in place about casing 12 with straps or ties 32. A sensor 20 is mounted within protector 24 and is connected to cable 18A through pigtail 22 which is untaped from the spooled cable and plugged into the sensor. Another joint is made up to casing 12 and the previous casing section, with distributed pressure monitoring system 10 attached, is advanced through the slips as the monitoring system is connected to the next length of casing, and so on.

After the casing is set, it is cemented into place. See Fig. 1. The selection of cement 28 is important in the overall design. The diffusivity of the characteristic to be monitored should be greater in the formation than in the selected cement. Hydraulic diffusivity, " $\alpha$ " is a measure related to fluid and pressure migration and is defined as follows:

$$\alpha = \frac{\text{permeability}}{\text{porosity} \times \text{viscosity} \times \text{compressibility}}$$

where, for the cement:

permeability is the permeability of the cement;  
porosity is the porosity of the cement;  
viscosity is the viscosity of the water injected with the cement; and  
compressibility is the compressibility of the system, including the cement and the fluids injected therewith.

By contrast, thermal migration is a function of thermal conductivity as well as well fluid migration.

Axial separation of sensors in adjacent zones should be selected such that radial transmission from the

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borehole wall will greatly exceed axial transmission along the borehole between adjacent sensors. Stated differently and returning to the example of pressure measurement, the fluid and pressure transmission are a function of time, diffusivity, and distance, the relationship of which may be roughly approximated by the following equation:

$$\frac{d^2}{\alpha t} = C_1$$

where:

d = distance  
α = diffusivity  
t = time  
c<sub>1</sub> = constant

Applying this basic relationship to the geometry of the borehole, a maximum distance from the formation (borehole wall) to the sensor may be expressed as follow:

$$\frac{r_{\max}^2}{\alpha t} = C_1$$

where:

r = radial distance between the sensor and the borehole wall  
α = diffusivity of the cement  
t = time  
c<sub>1</sub> = constant

and the minimum spacing between adjacent sensors which controls the interference of pressure from selected zone migrating to another may be expressed as follows:

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$$\frac{l_{\min}^2}{\alpha t} = C_2$$

where:

l = axial distance between adjacent sensors

$\alpha$  = diffusivity of the cement

t = time

5                     $C_2$  = constant

Because of the non-linear nature of this relationship, pressure can be seen to be far more readily transmitted over short distances such as between the formation and the nearest sensor than over the moderate distances which separate adjacent sensors. This allows substantial isolation of data from adjacent formation zones intersected by the borehole with corresponding pressure sensors. The borehole is filled with a cement selected to provide less hydraulic diffusivity than that of the formation and the pressure tentacles are arranged such that, when cemented, they will come into close proximity with the borehole wall at least somewhere along the length of the pressure tentacle. The adjacent pressure sensors are nonetheless separated axially along the borehole such that the distance between pressure sensors makes the sensors relatively insensitive to axial pressure transmission through the cement when compared to radial pressure transmission from the borehole to the pressure tentacle.

Cement in drilling and completion arts is commonly made up from the following components: Class G cement, Cement Friction Reducer, mixed metal hydroxides, sodium silicate, flyash, silica flour, silica sand, fumed silica, spherelite, and bentonite gel. With this range of variables and the state of present documentation of

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characteristics, selecting an appropriate cement for a given application may involve a testing program with respect to time, temperature, permeability and compressive strength.

5       Cement selection and sensor placement may be more clearly illustrated by working through an example designing a distributed pressure monitoring system for application in a given well.

Illustrative Design Example

10       The graphs of Figs. 9-11 illustrate design parameters as conservatively modelled for application to a given well. In each of Figures 9-11 curves a, b, c, d, e relate to cement permeabilities of 0.001, 0.01, 0.1, 1, 10 repectively. Fig. 9 illustrates the basic relationship of  
15       pressure migration through cement as a function of percent pressure change (P), time (t), and cement permeability (assuming that cement selection holds porosity and compressibility substantially constant). Again, under these constraints, Fig. 10 models a range of  
20       cement permeabilities, time (days), and distance into cement (dc) based on a design criteria of 98% of the formation pressure being seen at the pressure sensor. The area A indicates how close to the formation the  
25       transducer must be to respond. Fig. 11 then models a range of cement permeabilities, time (years), and area B indicating distance between transducers based on a design  
30       criteria of no more than 5% of the pressure at a sensor in one zone migrating through the cement to reach the sensor at a second selected zone to introduce error into  
35       the measurements of formation conditions in the second zone.

      The optimal spacing between sensors (l) (see Fig. 1) is determined after a cement permeability is selected. The selected permeability must allow a rapid sensor  
35       response time (compared to process time for well

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management techniques to be practiced) while minimizing the error in pressure response due to communication through the cement between sensors. In this example, cement permeability greater than 0.001 md allows a response time of less than 10 days through 1/2 inch of cement (r) and cement permeability less than 0.03 md allows sensors 50 feet apart (l) to remain isolated (to within 5% error) for more than one year. The cement was formulated to be 0.01 md to balance these two criteria.

The importance of the pressure tentacle as a means to control (r) is apparent in designing such a system, e.g., calling for mounting sensors on a 5" casing within an 11 1/2" borehole. The pressure tentacle ensures an effective pressure conduit that is adjacent the formation and not affected by any minor, very localized variations in the cement mixture.

Fig. 8 illustrates the pressure gradient in a well as a function of pressure, depth, and time as is particularly useful for reservoir management. Here the pressure at selected lower zones is shown to drop over time. Excessive drop at any given zone may lead to formation compaction which can collapse the casing. Thus, the sensor array provides notice of pressure depletion which retards oil production and can lead to well failure. Timely access to this data allows adjustments in pumping schedules and/or secondary recovery operations to protect the well and to maximize production efficiency.

Figs. 6 and 7 illustrate a special application of distributed pressure monitoring system 10 to monitor cement jobs for secure seals against the casing. The casing is set with the distributed monitoring system in place. The mud stabilizing the formation and controlling the well has a density indicated on the graph at region 100. The mud is displaced with a water/surfactant slug

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which appears as a sharp drop 102 which is followed by pumping cement down the casing and up the annulus of the borehole which appears as a sharp rise in density at 104. After the column of cement is in place, it begins to set. This process begins with a rate of change on a positive curve 106, this appearing as a loss of density as solids settle out. However, at transition, this rate of change follows a negative curve 108 as mycels set and the weight of the column of cement begins to transfer to the borehole wall and the casing. See Fig. 1.

Returning to Figs. 6 and 7, the maximum formation pressure 110 may be historically available, or may be observed after the cement sets fully and formation pressure migrates through the cement to pressure sensors. The critical difference illustrated between Figs. 6 and 7 is that the cement transition of Fig. 6 is above the maximum formation pressure. That is, the cement develops structural integrity before it is overburdened with formation pressure which will result in a failed cement job which permits annular gas flow. Contrast Fig. 7 where such failure was predicted and remedial action was required in the form of a "squeeze job" in which cement is injected into the pathway of the annular gas flow. Having contemporaneous access to this data not only predicts when remedial action will be required, but allows the design of the next cement jobs in the field to better meet the needs of the formation.

The foregoing description is merely illustrative of some embodiments of the present invention and many variations are set forth in the preceding discussion. Further, other modifications, changes and substitutions are intended in the foregoing disclosure and in some instances some features of the invention will be employed without a corresponding use of other features. Accordingly, it is appropriate that the appended claims

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be construed broadly and in the manner consistent with the spirit and scope of the invention herein.

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C L A I M S

1. A system for monitoring a characteristic of an earth formation into which a wellbore is formed with a casing fixed in the wellbore by a layer of cement between the casing and the wellbore wall, said characteristic being transferable through at least part of the thickness of the cement layer, the system comprising:
- 5
- at least one sensor for measuring said characteristic, each sensor being attached to the casing and including sensing means extending into the layer of cement; and
  - 10 - means for transferring signals representing said characteristic from the sensor to a selected surface facility.
2. The system of claim 1, wherein said characteristic is at least one of the formation pressure, the formation temperature and the formation fluid composition.
- 15
3. The system of claim 1 or 2, comprising a plurality of said sensors spaced along the casing.
4. The system of any one of claims 1-3, wherein said means for transferring signals comprises a communications line extending along the casing to said surface facility, each sensor being connected in communication with the communications line.
- 20
5. The system of claim 4, wherein each sensor is connected in communication with the communications line by means of a pigtail.
- 25
6. The system of any one of claims 1-5, wherein each sensor is enclosed by a sensor housing.
7. The system of claim 6, wherein each sensor is protected by a protector, each protector comprising a collar securely engaged about the casing and a pair of

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axially oriented plates extending from the collar so as to receive the sensor housing pertaining to the sensor.

8. The system of claim 7, wherein the protector further comprises a plurality of radially extending,

5 substantially axially oriented centralising fins projecting from the collar.

9. The system of any one of claims 1-8, wherein said at least one sensor includes a pressure sensor for measuring the formation pressure.

10 10. The system of claim 9, wherein each pressure sensor comprises a pressure transducer including a diaphragm, a conduit leading to the diaphragm and a pack of silicone grease in the conduit in communication with the diaphragm.

15 11. The system of claim 10, wherein the sensing means of the pressure sensor comprises an open pressure tentacle including a permeable wire mesh hose which is at one end thereof closed at the other end thereof connected to said conduit, a gravel pack located within the wire mesh hose, and a frit located in the conduit between the pack of  
20 silicone grease and the gravel pack.

12. The system of any one of claims 9-11, comprising a plurality of said pressure sensors spaced along the casing, wherein the sensing means of the plurality of  
25 sensors are separated by a distance along the borehole such that the sensors are relatively insensitive to axial pressure transmission through the cement when compared to radial pressure transmission from the wellbore to the sensing means.

30 13. The system of claim 12, wherein the hydraulic diffusivity of the cement and the spacing of the sensing means are adjusted such that the time scale for pressure communication from the formation to the sensing means is small compared with communication between adjacent  
35 sensing means.

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14. The system of any one of claims 9-13, wherein the hydraulic diffusivity of the cement is less than that of the formation.

5 15. The system of any one of claims 1-14, wherein said at least one sensor includes a temperature sensor for measuring the formation temperature.

16. A method of monitoring a characteristic of an earth formation into which a borehole is formed, the method comprising:

10 a) attaching at least one sensor having sensing means for measuring said characteristic to a casing which is to be installed in the borehole, the sensing means being arranged such as to extend between the casing and the borehole wall when the casing is installed in the  
15 borehole;

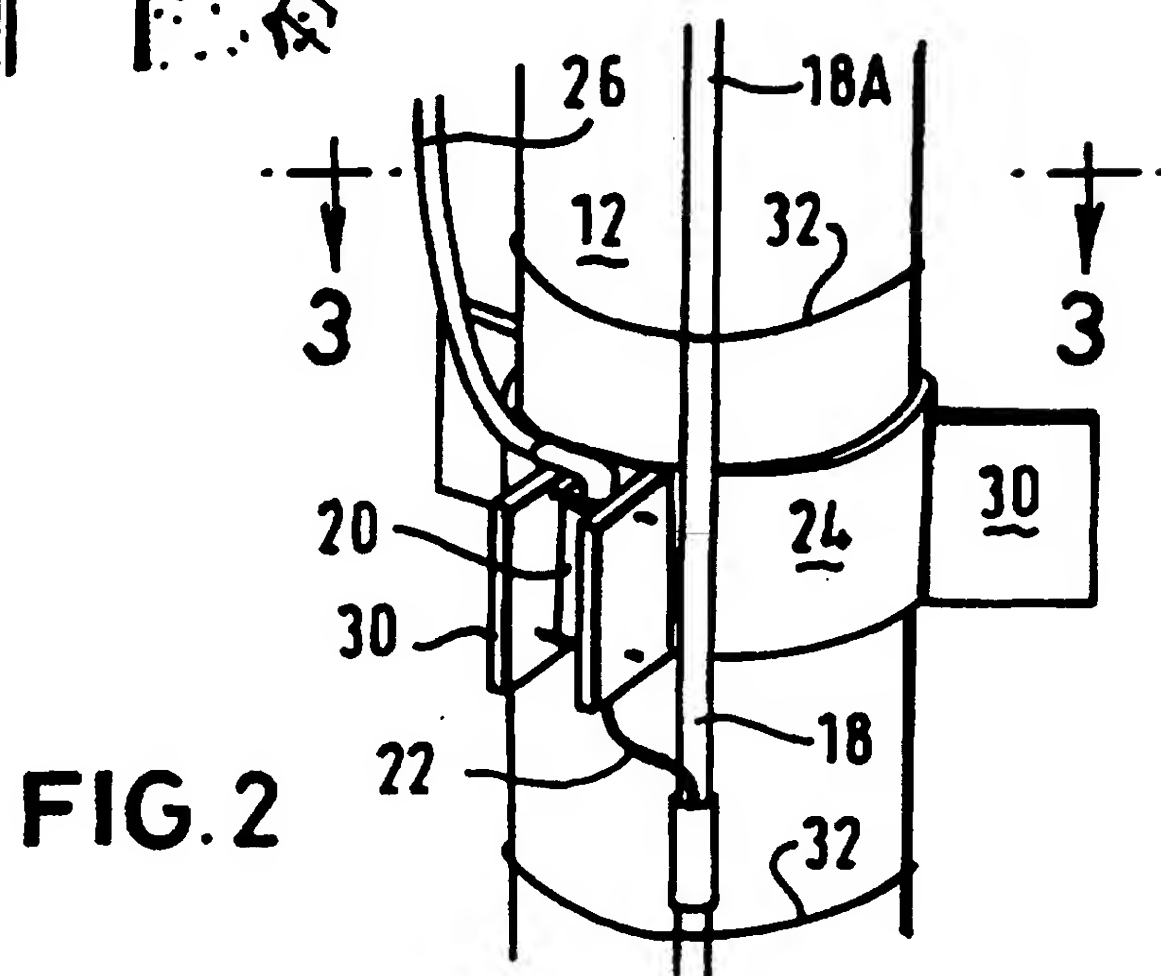
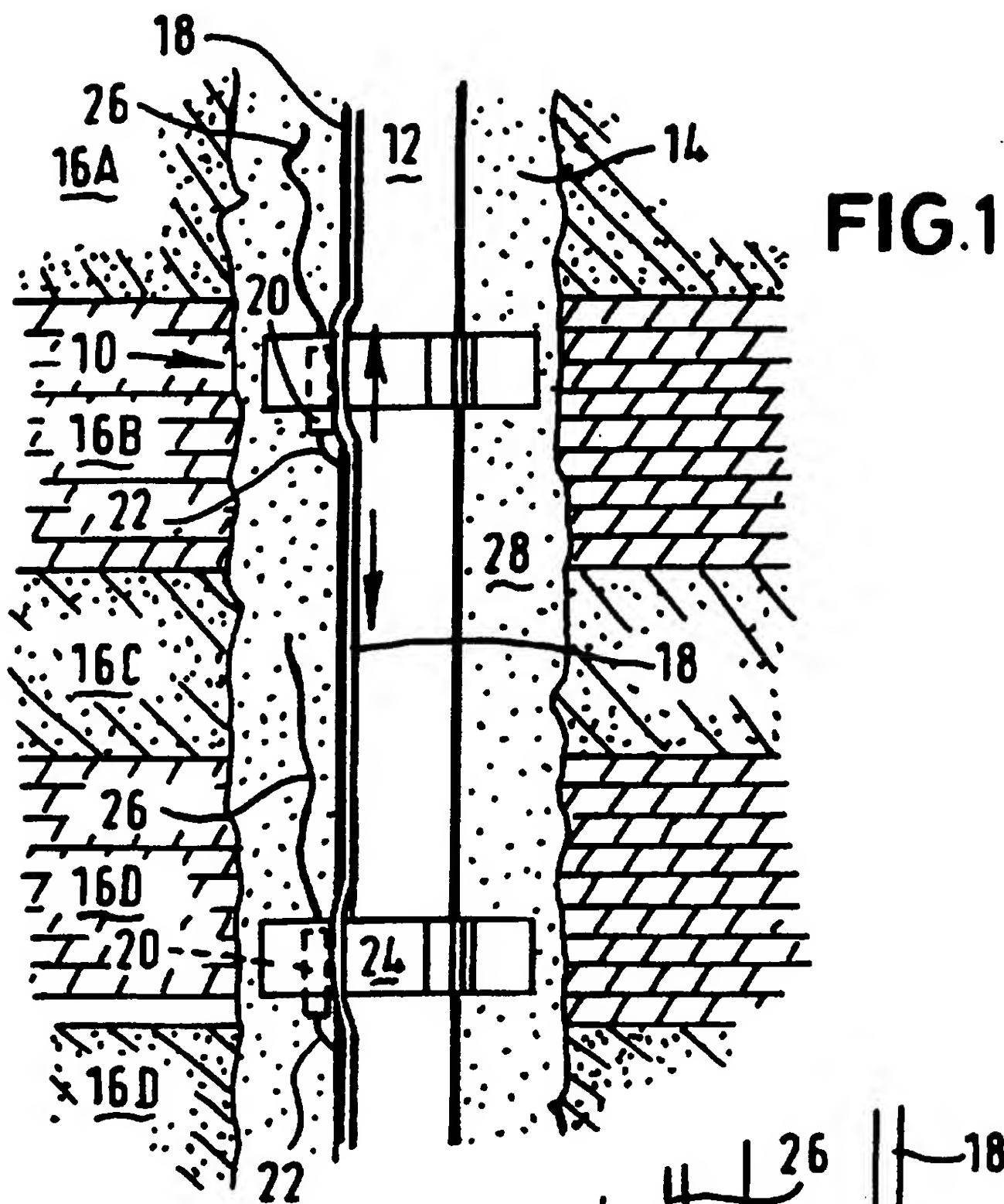
b) providing means for transferring signals representing said characteristic from the sensor to a selected surface facility;

c) lowering the casing into the borehole;

20 d) selecting a cement for cementing the casing in the borehole so that said characteristic is transferable through at least part of the thickness of the cement layer formed when the casing is cemented in the borehole;  
e) cementing the casing in the borehole whereby the  
25 sensing means becomes located in the cement layer between the casing and the borehole wall.

17. The method of claim 16, wherein step b) includes strapping a multi-wire cable to the casing as the casing is made up and lowered into the borehole.

30 18. The method of claim 16 or 17, wherein step a) comprises attaching a plurality of said sensors at spaced intervals along the casing, the locations of the sensors corresponding to a plurality of zones of the earth formation to be monitored.



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FIG.4

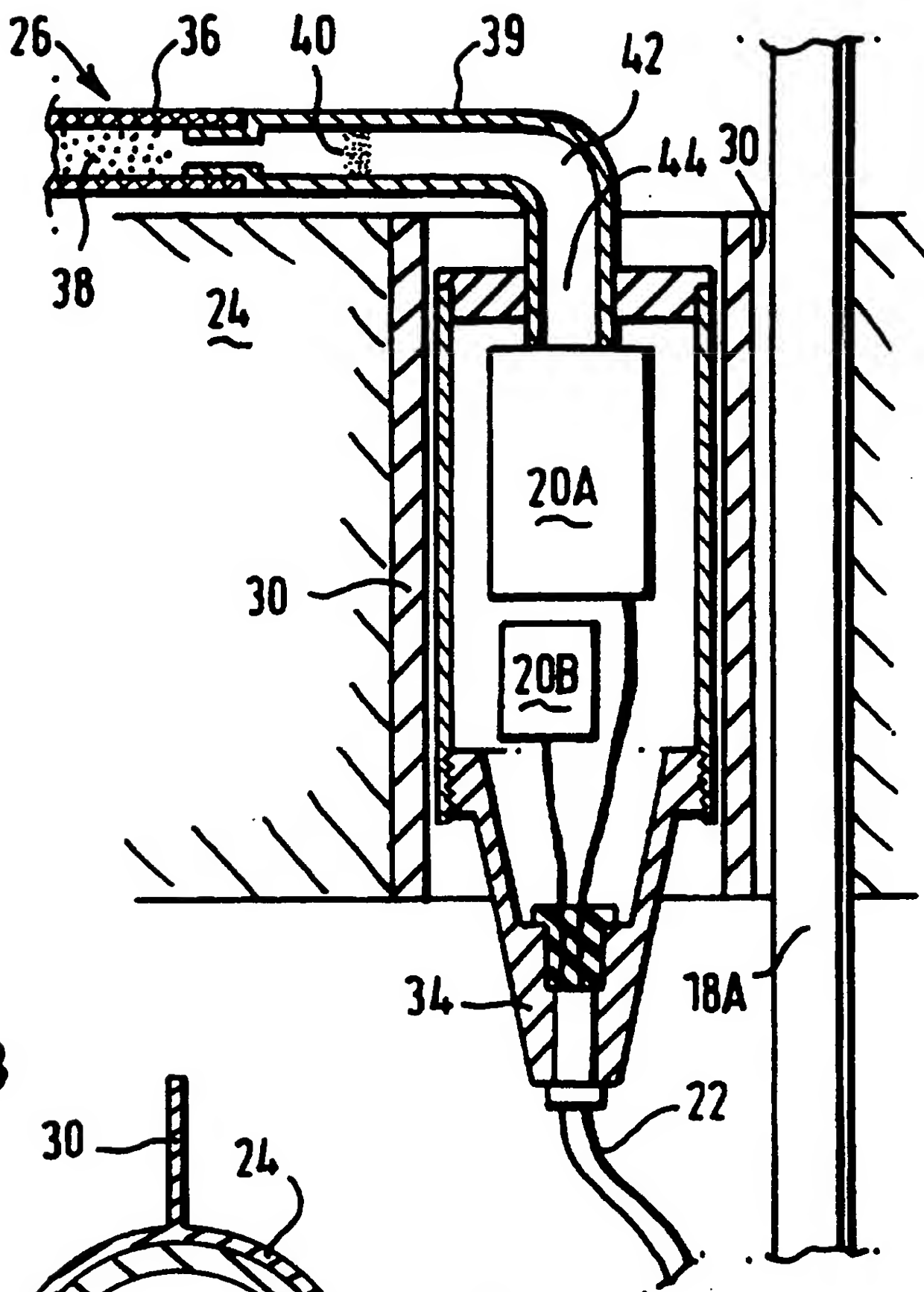
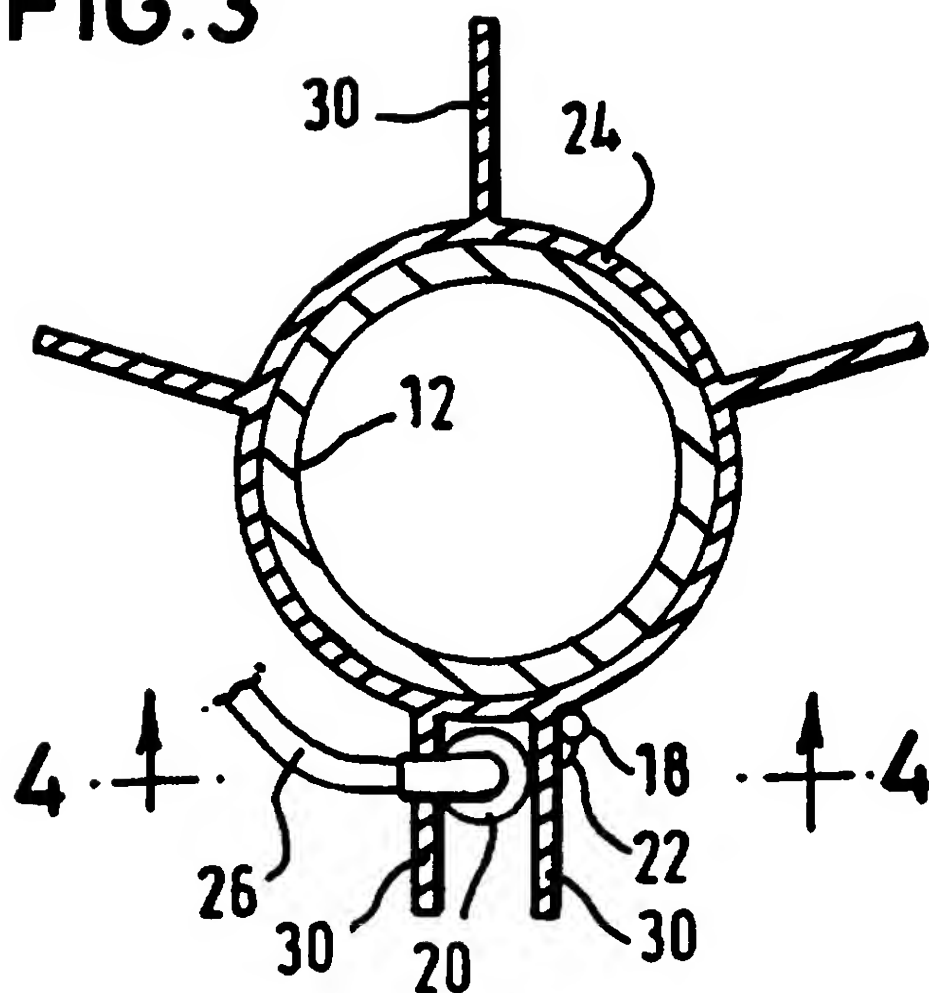
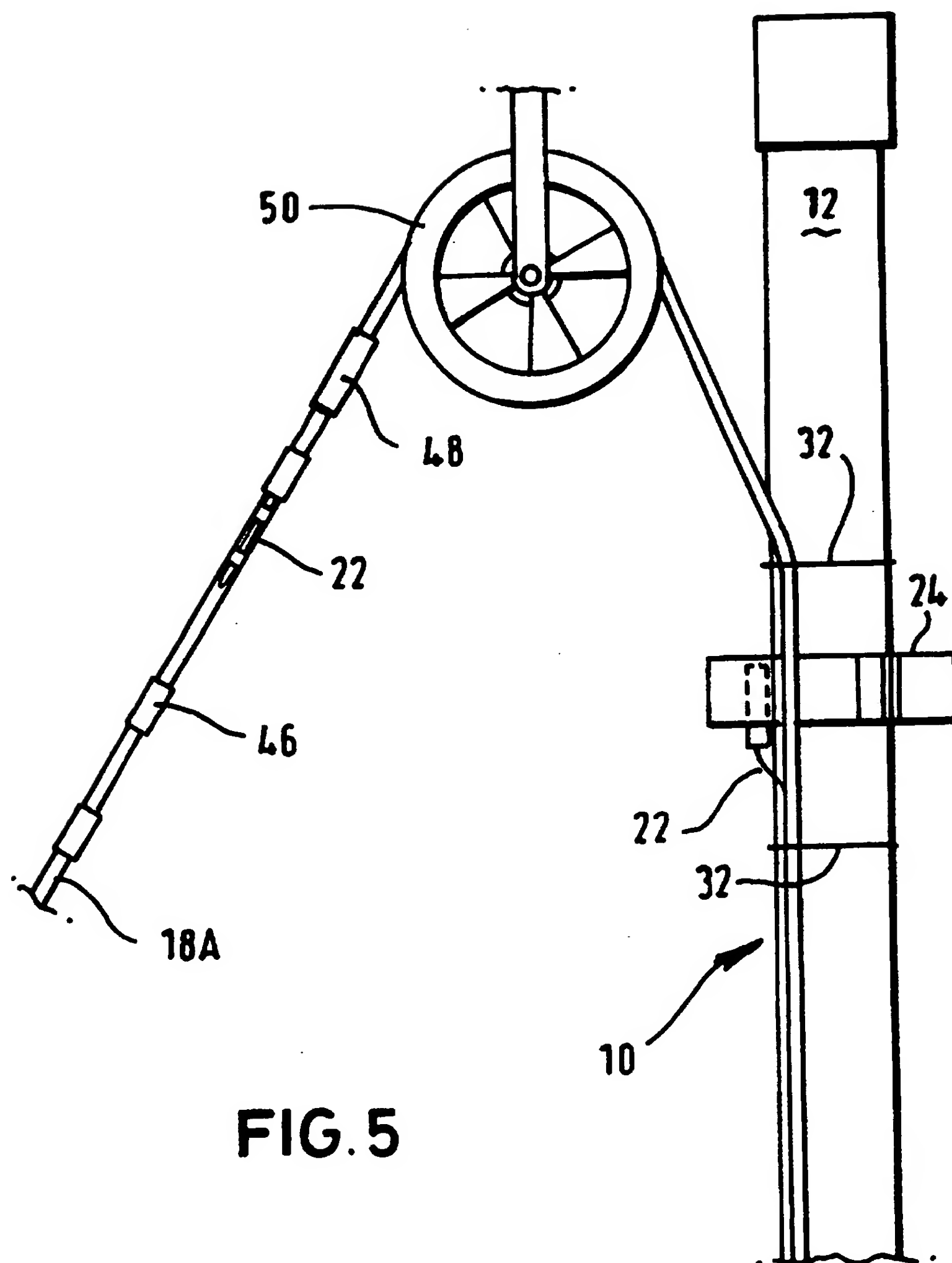


FIG.3

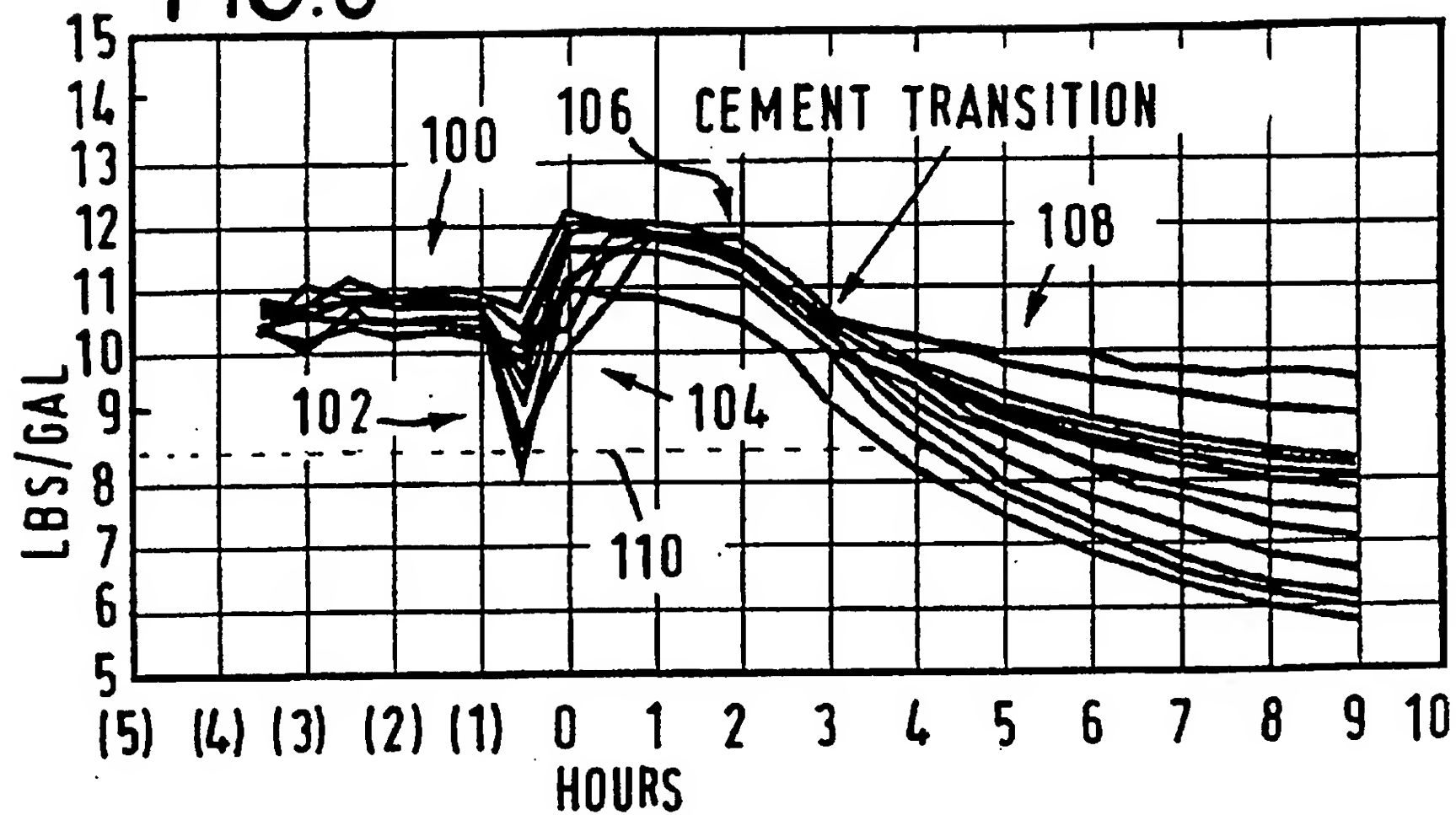




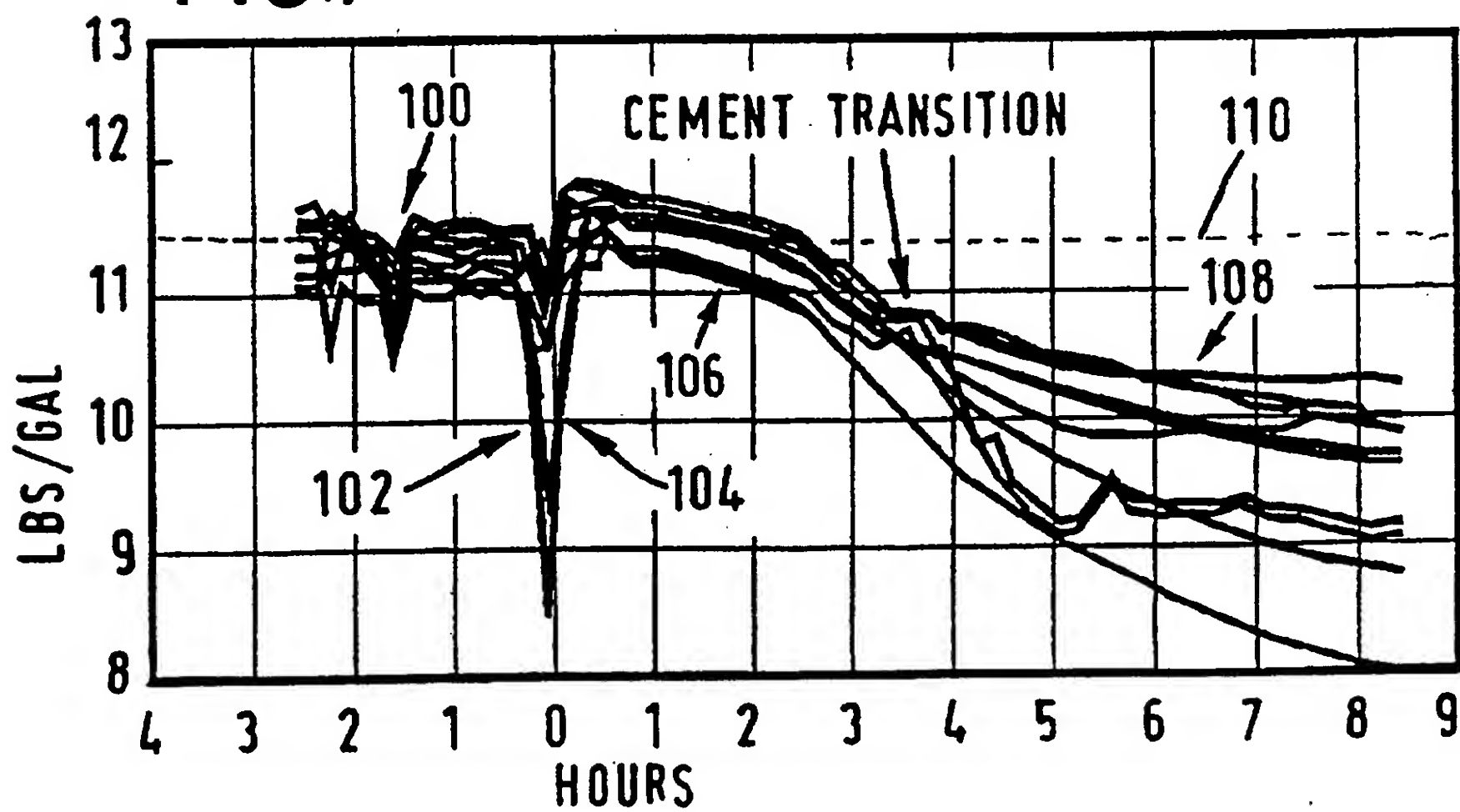
**FIG. 5**

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**FIG.6**



**FIG.7**



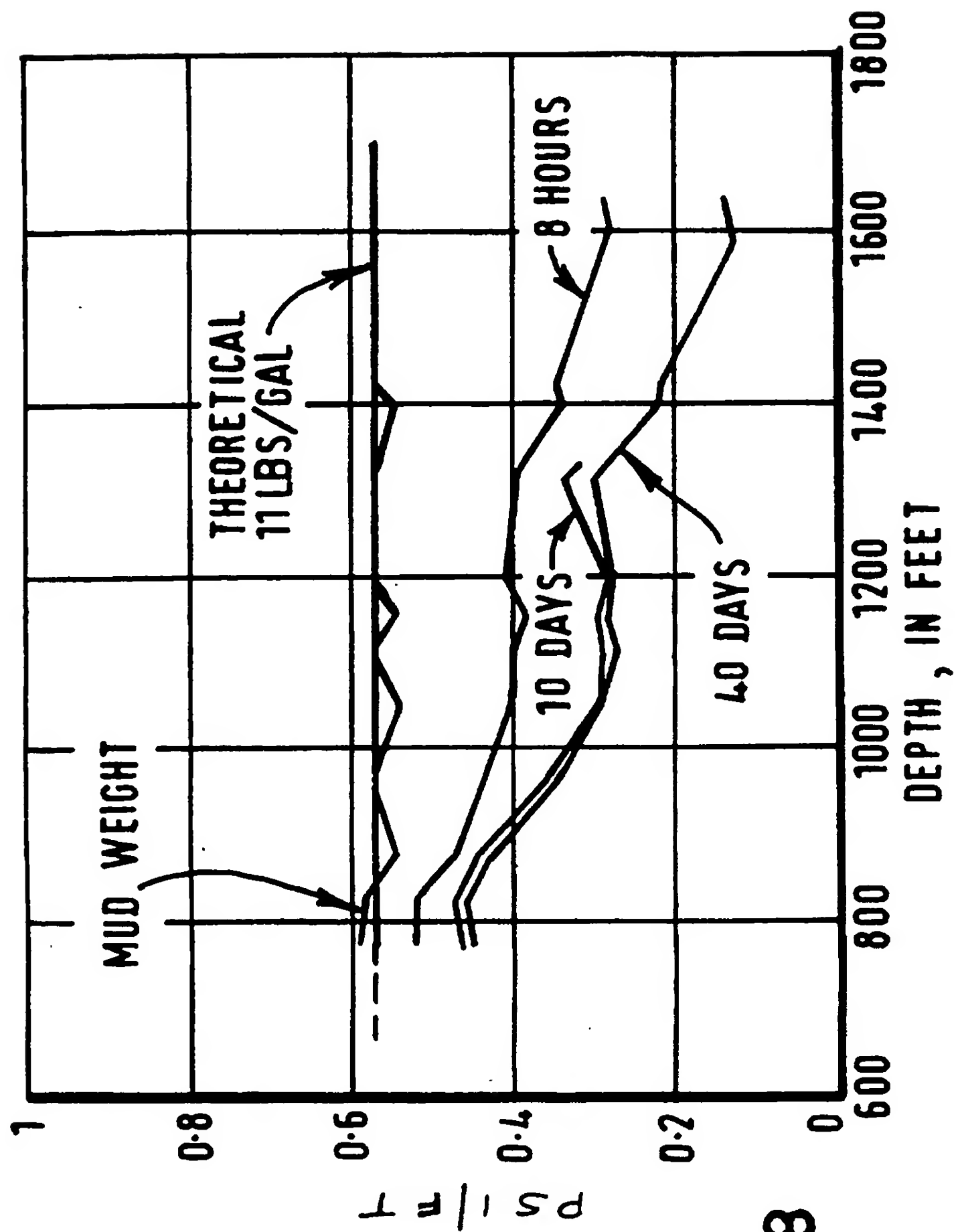


FIG. 8

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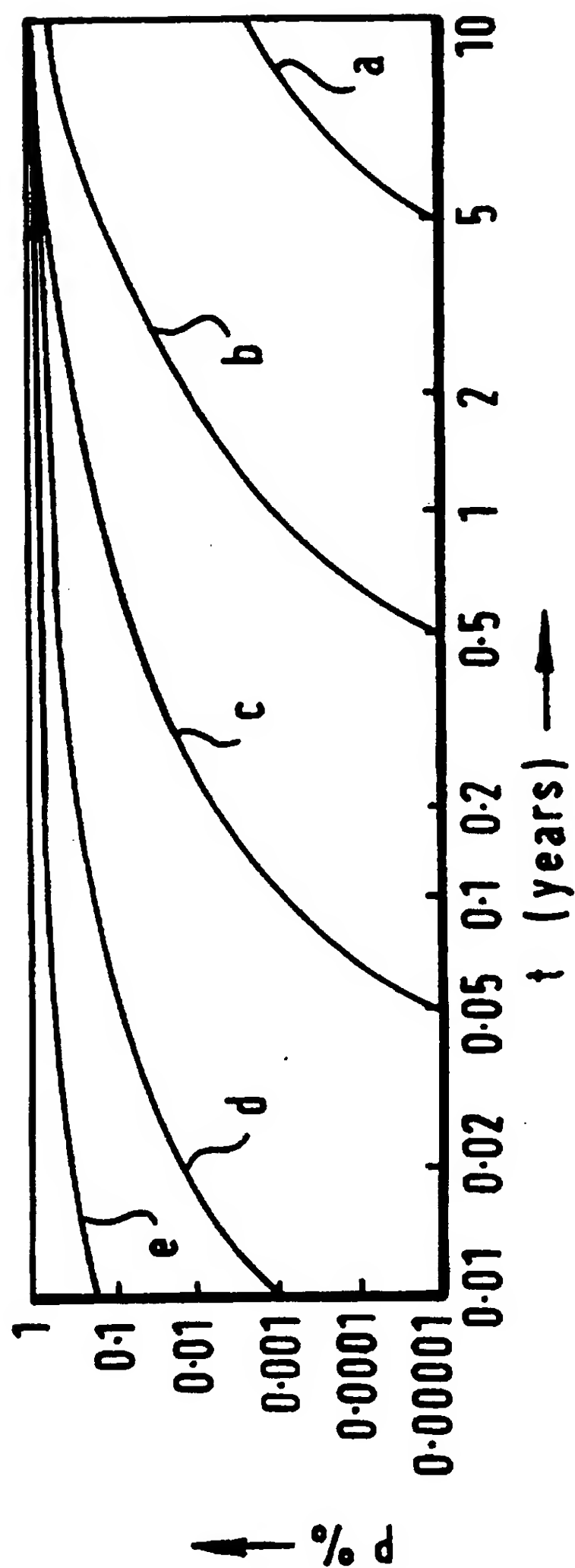


FIG. 9

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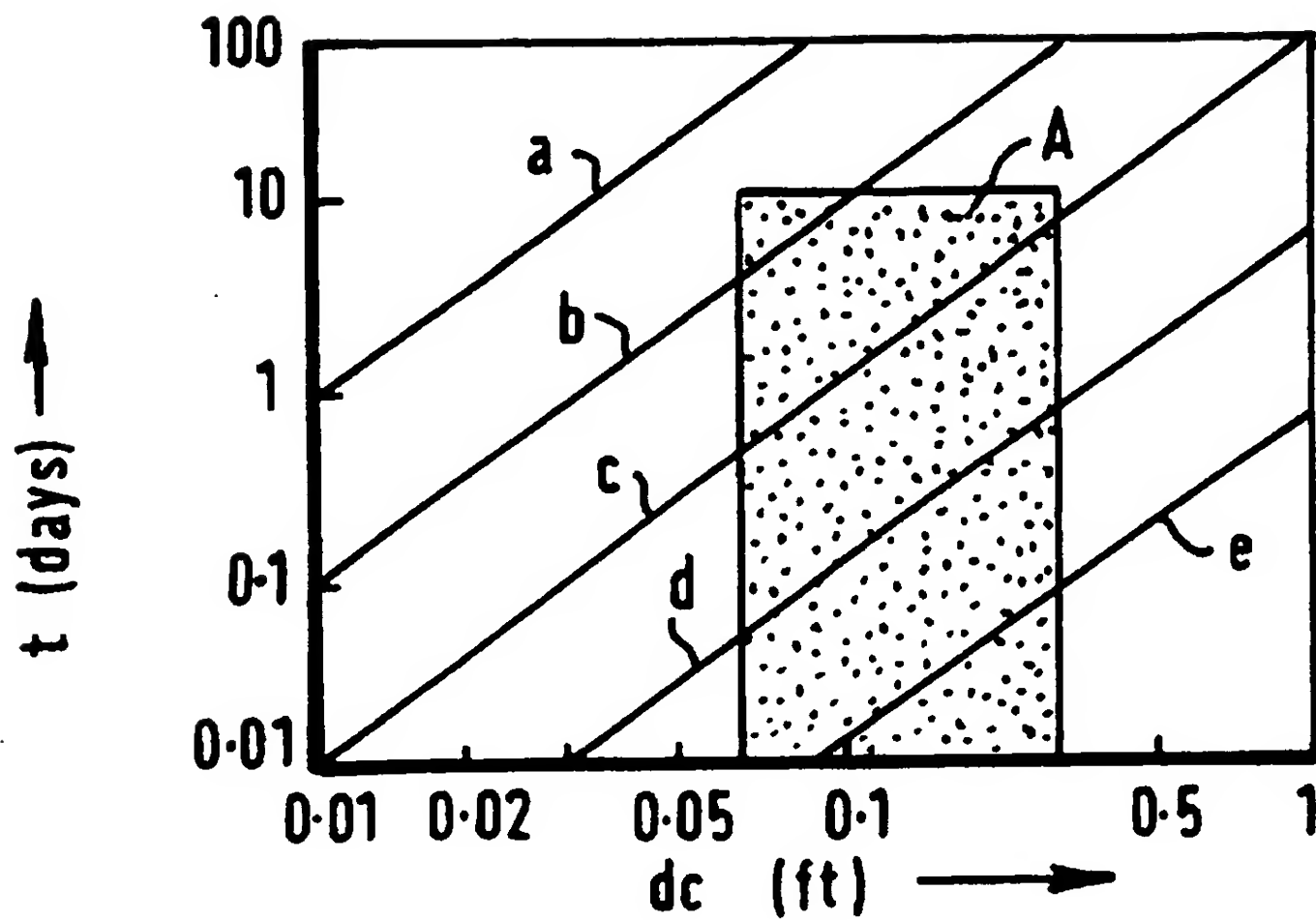


FIG. 10

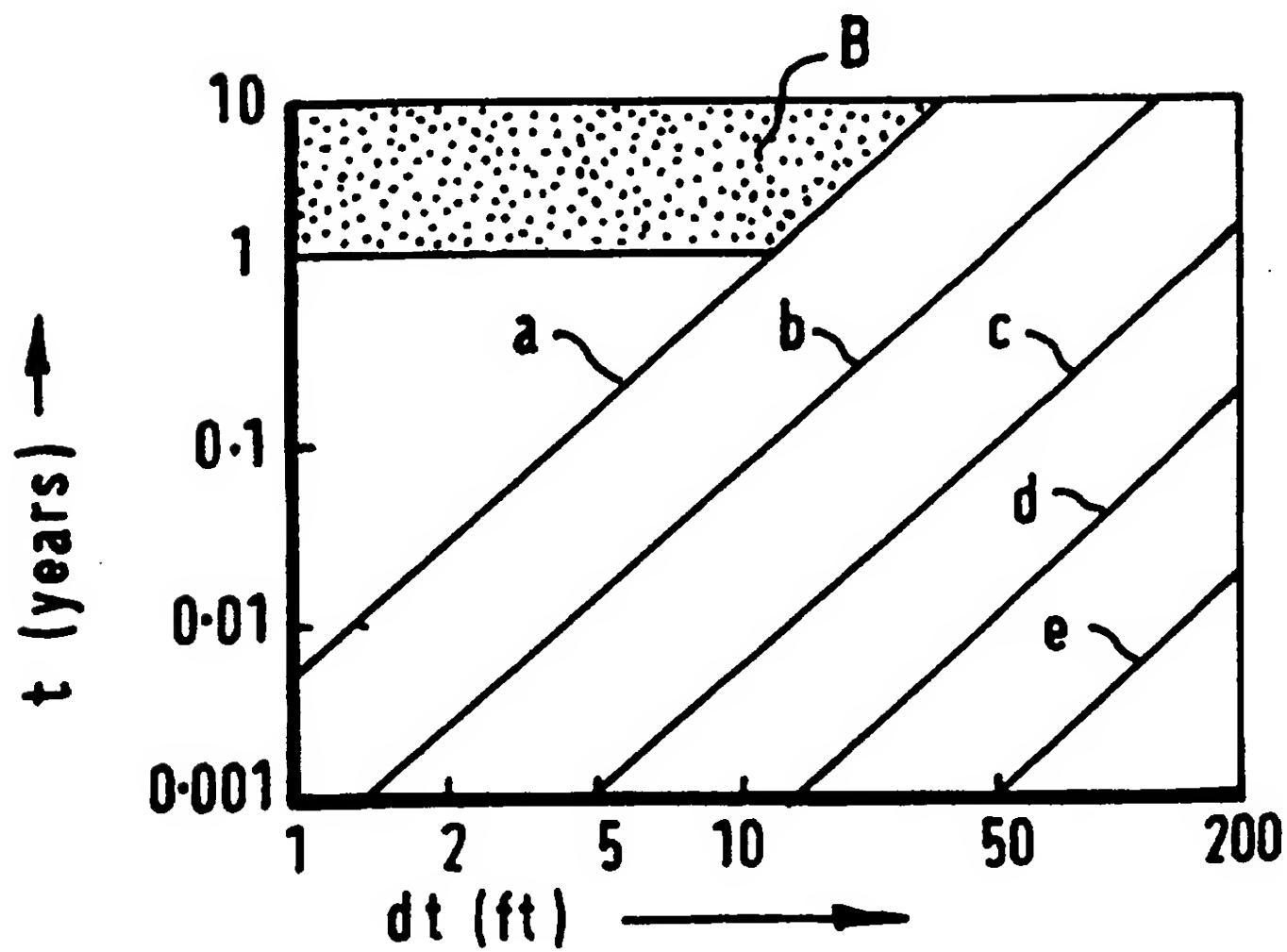


FIG. 11

# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/EP 97/01621

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 6 E21B47/01 E21B33/14 E21B47/06

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 6 E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4 775 009 A (WITTRISCH) 4 October 1988 see abstract see column 1, line 63 - column 2, line 3 see column 2, line 37 - line 41 see column 3, line 50 - line 52 see column 3, line 68 - column 4, line 2 ---	1,16
A	US 5 142 471 A (DESBRADES) 25 August 1992 see abstract ---	1,16
A	US 4 662 442 A (DEBREUILLE) 5 May 1987 see column 3, line 20 - line 22 see column 3, line 4 - line 15 see column 2, line 59 - line 66 ---	1,16
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☒ Further documents are listed in the continuation of box C.

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# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/EP 97/01621

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Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 1 582 241 A (BRITIH PETROLEUM COMPANY LIMITED) 7 January 1981 see page 2, left-hand column, line 20 - line 34 ---	1,16
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Information on patent family members

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